



Is 30 km/h a 'safe' speed? Injury severity of pedestrians struck by a vehicle and the relation to travel speed and age

Höskuldur R.G. Kröyer *

Department of Technology and Society, Lund University, Sweden

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ABSTRACT

This study uses Swedish accident data for the years 2004–2008 to analyze the relationship between injury severity for pedestrians struck by a vehicle and the speed environment at accident locations. It also makes use of a multinomial logit model and other statistical methods. Speed measurements have been performed at accident sites, and the results show that there was a relationship between the (1) mean travel speed and (2) the age of the pedestrian struck and the injury severity and risk of fatality. The data also shows that even though fatal accidents (excluding run-over accidents) are rare in speed environments where the mean travel speed is below 40 km/h and severe injuries are rare below 25 km/h, over 30% of severe injury accidents occur in speed environments below 35 km/h. This indicates that 30 km/h speed limits might not be as safe as previously believed. The current speed policy needs to address this issue. To the author's best knowledge this is the first study that analyzes the relation between mean travel speed and injury severity for pedestrians struck by vehicles.

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1. Introduction

When a pedestrian is struck by a motorized vehicle, then there is a considerable risk of injuries. The severity of those injuries and the probability of survival are highly dependent on several factors such as the age of the pedestrian [1–3], the vehicle type [4–6] and the impact speed [7–10]. The impact speed is the most direct way to measure the force of the impact and to obtain a statistically significant relation with the injury severity (see [11] for example). However, since it is hard to use that relation to formulate speed management strategies, speed limits and travel speeds remain more 'relevant'. The aim of this study is to analyze how the injury severity and fatality risk in pedestrian–vehicle accidents are related to the mean travel speed and the age of the pedestrian, and thereby improve the scientific basis for speed policies.

2. Literature review

When a pedestrian is struck by a motorized vehicle there is a complex chain of events. Each impact (with the vehicle and the ground) on the pedestrian's body and the resulting acceleration/deceleration

has the potential to cause injuries. The location of the impact and its force are important since different parts of the body can sustain injuries differently and have different thresholds for injuries [12]. This means that the injury outcome is dependent on, for example, (i) the properties of the pedestrian [13,14] (height, direction vis-à-vis the vehicle and initial position) that will affect where the impacts will be, (ii) properties of the vehicle [5,14,15]: the shape of the vehicle will affect where the impacts will be and the stiffness of the vehicle can affect how blunt the impact will be and (iii) the impact speed [12,16] will affect both the chain of events and the bluntness of the impact.

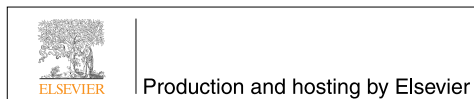
The literature review shows that the risk of severe injuries is higher for Sport Utility Vehicles (SUVs), Light Truck Vehicles (LTVs) and trucks compared to passenger vehicles [4,17–19]. The fatality risk is also higher for LTVs and SUVs compared to passenger vehicles [4–6,18,20]. Three design factors where the SUV and LTV differ from the passenger vehicle affect the mechanisms of the collision: they are stiffer, have higher bumpers and are heavier [5]. Other studies have pointed out that it is not the weight, but rather the front structure that affects the injury severity [21]. Since the weight of any vehicle is so much greater than the weight of a pedestrian, the resulting acceleration for the human body in an impact can hardly make a significant difference.

The impact speed can influence the impacts between the pedestrian and vehicle and between the pedestrian and ground [12]. It is also the most direct variable with which to analyze the size of the forces involved in those impacts. Several studies have shown that the risk of severe injuries [7,10,18,22–24] and the risk of fatality [8–10,25,26] are dependent on the impact speed. Even though the resulting fatality risk values vary among the studies [27,28], they uniformly show that the fatality risk increases rapidly with higher impact speed, and that a

* Tel.: +46 46 222 9198; fax: +46 46 222 9100.

E-mail address: hoskuldur.gudjonsson@tft.lth.se.

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10 km/h increase in impact speed will result in doubling of the fatality risk at urban speed levels [27].

Those two factors combined (chain of events and the force of impact) affect where on the body the sustained injuries will be and how blunt the impact will be. However, the severity of the resulting injuries will also be influenced by the pedestrian's individual properties and injury threshold. This injury threshold may vary between individuals; for example a light collision or light impact might not cause any injuries to a young pedestrian, while the same impact might cause severe injuries to an older and less physically strong pedestrian. Previous research shows that the risk of severe injuries is higher for seniors compared to younger adults [1,7,17,19]. The prognosis of those injuries is also highly individual and dependent on, among other things, the time to medical treatment and the quality of it [29,30]. This individual difference is often studied according to age, i.e. the survivability is highly related to the age of the victim. Previous studies have found that seniors have a higher risk of fatality compared to younger adults [1–3,19,20]. This difference becomes even higher if the data is weighted with regard to vehicle type, impact speed and other individual factors [1].

This study applies mean travel speed instead of impact speed (which has been applied in earlier studies). Even though this will weaken the relation between the force of the impact and injury severity, it is of interest due to the fact that the travel speed is more practical for design and policy purposes. The relation between those variables requires some discussion. It stands to reason that there should be a relation between the travel speed and the impact speed; therefore it is logical to expect a relation between the travel speed and the severity outcome of an accident. Two studies are identified as analyzing the relation between the travel speed of the vehicle involved in an accident and the injury outcome. Leaf and Preusser [31] analyzed data material from FARS (Fatality Analysis Reporting System) and GES (NHTSAs General Estimates System) and accident data material from Florida, and Pasanen and Rosén [32] analyzed the data material from GIDAS (German In-depth Accident Study). Both studies showed that the fatality risk increased rapidly with higher travel speed of the vehicle involved in the accident. Still, it is problematic that the travel speed of the vehicle is often not known or known with poor precision [31]. Studies often use speed limits as a proxy for the travel speed, and several found a relation between the fatality risk and the speed limit [4,29,31,33]. The literature review has revealed only one study that did not find a relation between the frequency of injuries and the speed limit [34]. This study [34] only referred to fatal accidents, but ascertaining the influence of different speed limits on injury severity requires including non-fatal accidents, otherwise the data material will be biased that can result in biased frequencies of severe injuries and misleading conclusions. It can therefore be concluded that the literature indicates a relation between speed limits and the fatality risk of struck pedestrians. This would also indicate that a relation can be expected between the speed level (expressed as mean travel speed) and the injury severity of an accident. To our knowledge no study has tried to analyze this relationship in terms of pedestrians struck by vehicles. It is certainly important to get a more 'complete' picture of the influence of speed level on injury outcome in order to compensate for the limitations of studies based on speed limits. Compared to the speed limit, the mean travel speed has the advantage that it often differs considerably from the speed limit, for example at intersections.

3. Data

The study is based on two separate datasets that were acquired from the STRADA database (Swedish Traffic Accident Data Acquisition). The aim of STRADA is to collect police and hospital reports for all accidents that occur in Sweden (currently STRADA does not get data from all regions of Sweden). This accident data is not as detailed, though, as in-depth accident databases, and therefore cannot be used to estimate impact or travel speed in accidents.

Dataset 1 includes all injury accidents where a pedestrian was struck by a motorized vehicle (collisions with motorbikes were excluded) in Sweden between 2004 and 2008 and the age of the pedestrian was known. The aim of dataset 1 is to have extensive data material to analyze the interrelation of the age of the struck pedestrian, the vehicle type and the injury severity. Dataset 2 has been created by drawing accident locations at random from dataset 1 within each severity group. Those accidents have had to fulfill the following additional criteria:

- (1) The accident had to have occurred in Scania (the most southern part of Sweden, and the one that has the most comprehensive data registered in STRADA).
- (2) If the injury was non-fatal, then a hospital report was required to be able to estimate the severity of the injury. Cases with 'no injury' (ISS = 0) were excluded from the dataset.
- (3) No icy or snowy road conditions or fog at the time of the accident.
- (4) The accident had to have occurred between 7 am and 7 pm to minimize the effects of speed differences between day and night.
- (5) Accidents where the injury severity was deemed not to be speed related (for example run-over accidents, where the vehicle travels over the pedestrian) were excluded.
- (6) If the accident report mentioned that there was a special situation at the time of the accident (for example if the lane was blocked by a parked vehicle) that could be expected to have considerable effects on the travel speed of the vehicle involved in the accident, the accident was excluded.
- (7) The accident location and the direction of the vehicle involved in the accident had to be known.
- (8) If any considerable change of the traffic environment occurred after the time of the accident, which could have effects on the speed level, the accident was excluded.
- (9) For practical reasons, accident locations with very low traffic volumes (for example small residential streets, parking facilities and reversing accidents) were excluded.

An overview of the numbers and proportions of accidents within each severity group is shown in Table 1. Injuries with an Injury Severity Score (ISS) between 1 and 8 are defined as minor injuries and injuries with ISS ≥ 9 are defined as severe injuries. Dataset 2 is stratified, with overrepresentation of severe injuries and fatal injuries. This needs to be kept in mind when looking at the results.

4. Method

Spot speed measurements were performed on the traffic flow in the same direction of travel as the vehicle that was involved in the accident at all accident locations in dataset 2, i.e. if the vehicle involved in the accident was turning from street A to street B, then only the speed of vehicles in this turning traffic flow was measured. Only the speed of vehicles in free flow was measured (at traffic signals and pedestrian crossings only those who were unaffected by the red amber or pedestrian flow). The lowest number of speed measurements per accident site was 59; in most cases there were more than 100 speed measurements, which should give a reliable estimation of the mean speed at each individual site (Table 2).

A multinomial logit model was applied on dataset 2. Due to the stratification of the dataset, the regression had to be weighted. According to Washington et al. [35], only the interceptor in this case will be affected,

Table 1
Accidents with different severities in the two datasets.

	Dataset 1	Dataset 2
Minor injuries	6474 (79.3%)	31 (39.2%)
Severe injuries	1420 (17.4%)	29 (36.7%)
Fatal injuries	272 (3.3%)	19 (24.1%)
Total	8166	79

Table 2

The mean speed and age of struck pedestrians for different injury severity classes in dataset 2.

	Mean speed	Standard deviation	Mean age of struck pedestrian	Standard deviation
Minor injuries	36.6 km/h	11.7 km/h	41.4	26.5
Severe injuries	40.5 km/h	12.6 km/h	55.5	30.2
Fatal injuries	48.9 km/h	15.8 km/h	65.2	24.7

and it can be corrected by subtracting $LN(\text{fraction outcome } j \text{ in sample} / \text{fraction outcome } j \text{ in population})$ from the intercept. The weighting factors were based on accidents in dataset 1 that fulfilled criteria (1) to (4), which gives the risk function in the form shown in Eq. (1).

$$P_i(v_i) = \exp(v_i) / \sum (\exp(v_j)). \quad (1)$$

$P_i(v)$ is the probability of injury severity i , v is a utility function that has been weighted and is dependent on the vehicle speed and age of struck pedestrian (and other variables in the model such as vehicle type and interaction variables). The parameters for the multinomial logit model were estimated by SPSS 20.

5. Results

The results are presented in four sections: influence of speed level, influence of age, the vehicle type and combined effects.

5.1. The influence of speed level on severity outcome

Fig. 1 shows the cumulative distribution of mean speeds at the accident locations in dataset 2. It demonstrates that the minor injury accidents occur at locations with mean speeds up to around 55 km/h. Severe injuries seem to start to increase at higher mean speeds compared to minor injury accidents, but the two curves are very similar. There is no statistically significant difference in mean speeds between the locations with minor and severe injuries ($p = 0.114$). This is rather unexpected since higher travel speeds should result in higher impact speeds. Previous research (for example [22]) has shown that higher speed is to be associated with higher risk of severe injuries. This can possibly be attributed to the fact that the mean age of the pedestrians who suffer minor injuries is much lower than of those who suffer severe injuries (41.4 years compared to 55.5, $p = 0.030$), i.e. the minor and severe injuries occur in similar speed environments, but the age of the victims affects if the injury outcome is minor or severe. The mean speed at accident locations with fatal injuries differs from those at locations with minor injuries ($p = 0.003$) and severe injuries ($p = 0.031$). The difference in speed can be expected to be even greater considering that those who are fatally injured are much older (65.2 years)

compared to those who suffer minor (41.4, $p = 0.001$) or severe (55.5, $p = 0.117$) injuries, i.e. if the cumulative distribution curves would be age normalized, the difference would be greater.

Even though the risk of fatality increases with higher speed, the majority of interactions between vehicles and pedestrians are at urban speeds (while pedestrians are often separated from car traffic in higher speed areas), and exposure is therefore one of the main variables for determining the speed levels at which the accidents occur. 93% of the severe injury accidents occurred at locations with a mean speed below 50 km/h and almost half at locations with a mean speed below 40 km/h. 79% of the fatal accidents occurred at locations with a mean speed below 50 km/h and 63.2% at locations with a mean speed between 40 and 50 km/h.

The changes in absolute risk of injury severity can be loosely interpreted from the changes of the slopes of the cumulative curves of mean speeds in Fig. 1. For example, if the slope of the cumulative curve for fatal accidents is increasing proportionally faster than the slopes of the two other curves (i.e. the curve is turning, for example exponential increase), it means that the number of fatal accidents is rising proportionally faster than the number of non-fatal accidents, i.e. the proportion of fatal accidents (absolute fatality risk) increases at higher mean speed. If we compare the three cumulative curves, it seems that the severe injury curve begins an exponential increase at around 25 km/h, while the other curves are nearly linear. This indicates that the risk of severe injuries increases after the speed exceeds 25 km/h. The same applies to the risk of fatality after the mean speed exceeds 40 km/h. However, due to data sample size, this should be interpreted with caution.

There is usually only one vehicle involved in a pedestrian accident. The travel speed of that vehicle will influence the probability of an accident occurring and the final impact speed, if an accident cannot be thwarted. The impact speed will then have a direct relation with how severe the injuries will be (see Literature review section). There should also be a probabilistic relation between the travel speed of the involved vehicle and the mean travel speed at the site of the accident, i.e. if the mean speed at the site is higher, the probability that the vehicle will have a higher travel speed is higher. At the same time Kloeden et. al. [36] show that the relative risk of accident involvement where ambulance was required increased with higher speed relative to the speeds of control vehicles, i.e. cars traveling at higher speeds compared to other vehicles are more likely to be involved in severe accidents. Nonetheless, this does not exclude the possibility that the travel speed of the accident vehicle can be independent of the mean travel speed at the accident site; for example, the vehicle might be traveling slowly even though the mean speed is high at that accident location or vice versa. The analysis of dataset 2 shows that the variance of speed at the accident sites does not differ between the injury severity groups and does not show any statistically significant difference ($p = 0.39$, ANOVA) see Fig. 2. However, the relation between the mean travel speed and the speed of the individual vehicle will always be probabilistic, i.e. a

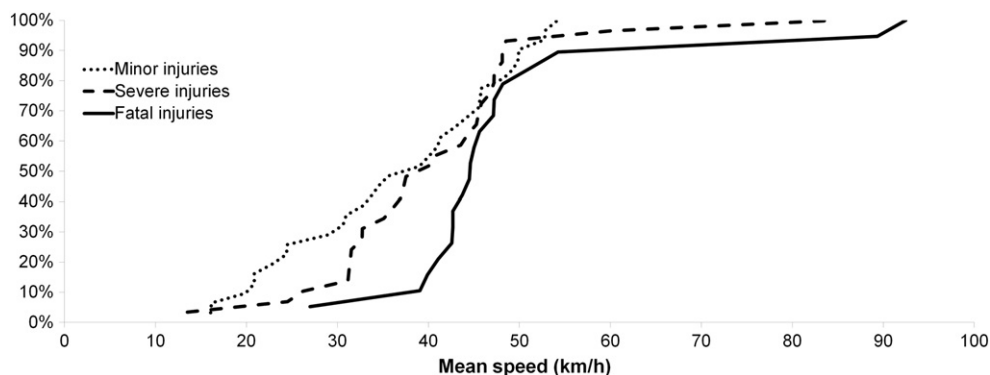


Fig. 1. Cumulative distribution of mean speeds at the accident locations by injury severity group in dataset 2.

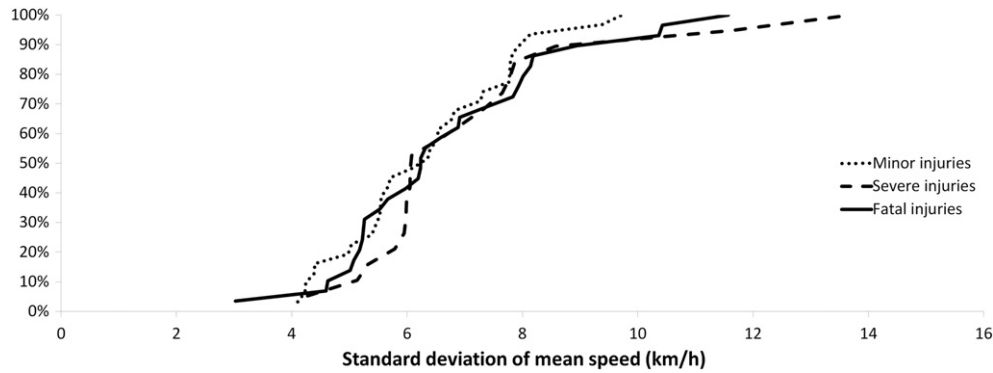


Fig. 2. The cumulative distribution of the standard deviation of the mean speed at accident locations by injury severity.

higher mean travel speed increases the probability of higher travel speed and higher impact speed for the vehicle involved in the accident. This approach, i.e. not to use the speed of the individual vehicle, does weaken the 'logical' relation between the accident and the travel speed variable. However, currently, in traffic engineering we influence the travel speed of the accident vehicle only indirectly through speed management, which influences the mean travel speed (and only has a probabilistic relation with the travel speed of the individual vehicle). Therefore, we require a good understanding of how mean travel speed influences the injury outcome. That knowledge has an 'indirect' relation to the speed of the accident vehicle and should not be considered as a replacement for the relations based on the speed of the individual vehicle, but rather as a complement of it. Thus, we may acquire a better understanding of the importance of all the different speed concepts so that our speed management policies can be more efficient.

5.2. The influence of age of struck pedestrian on injury severity outcome

Fig. 3 shows the cumulative age distribution for datasets 1 and 2 for the three injury severity groups. It shows that the age distribution is similar for the minor injuries for both datasets, however there seems to be some underrepresentation in dataset 2 for the age group 40 and 55.

There is also an underrepresentation in dataset 2 of severe injuries for the age group 20 to 50. If dataset 1 is limited to Scania (the geographical region dataset 2 is based on) then this underrepresentation disappears, i.e. dataset 2 is representable for Scania and the difference is due to differences between Scania and Sweden as a whole. For the fatal injuries there is a peak in dataset 1 in the age group 18 to 30 that is missing in dataset 2. Nationwide, there are 34 fatal accidents in this age interval. Twentyseven of the accidents occurred between 7 pm and 7 am and were therefore excluded. Two additional accidents are excluded because they were run-over accidents, but in those types of accidents then the injuries are not necessarily speed related. The explanations as to why the accidents were excluded in dataset 2 (Scania) are similar to those for the whole country and therefore the two datasets are compatible. Otherwise, the fatal injury curves are fairly similar. The age distribution is similar for both datasets, but dataset 1 is used for this analysis, as it is more comprehensive compared to dataset 2.

There might be a U shaped risk pattern regarding age (see Fig. 4A), where children have a high risk of severe injuries that reduce up to the age group 25 to 34. Then, after the age of 35 the risk of severe injuries starts to increase again. Fig. 4B shows the risk of fatal accidents. The risk of fatality seems to be slightly elevated for the youngest group, but the confidence intervals are wide for that age group due to relatively

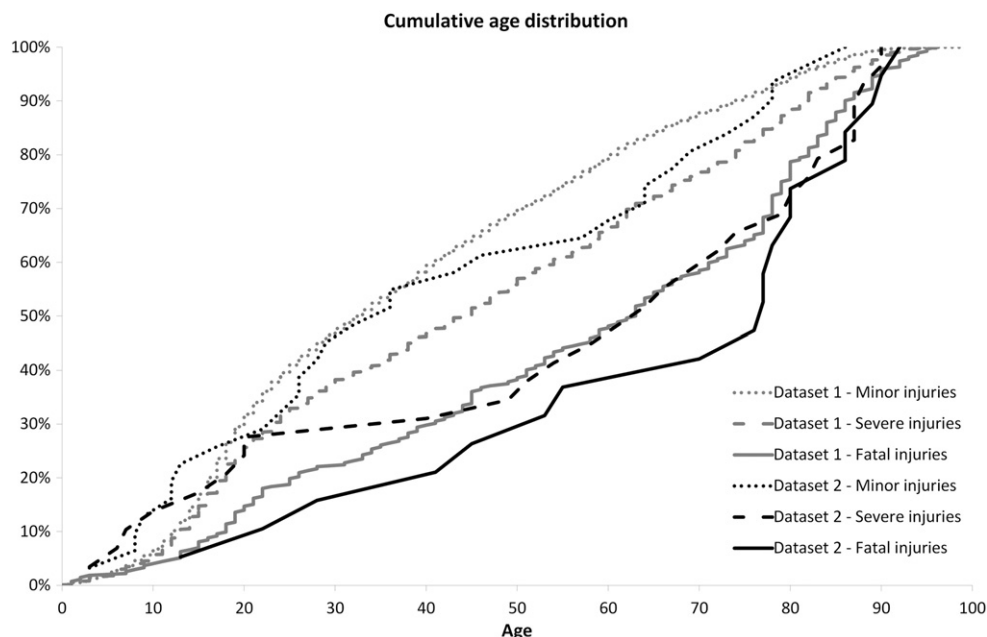


Fig. 3. Cumulative age distribution for dataset 1 and dataset 2.

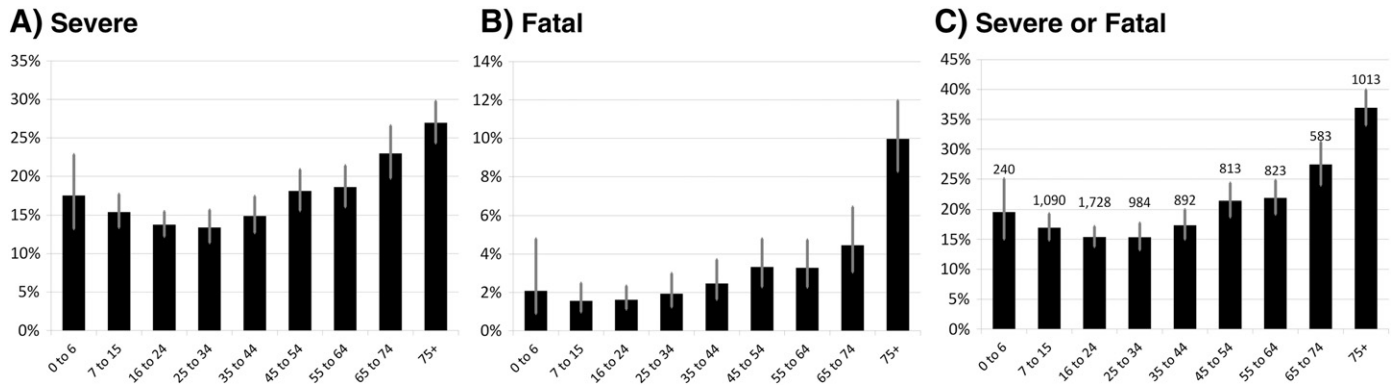


Fig. 4. Risk of A) severe injuries, B) fatal injuries and C) severe and fatal injuries by age groups for dataset 1. Confidence intervals (95%) are based on [37], and the numbers in panel C show the number of observations within each age group.

few fatal accidents. The fatality risk seems to start to ‘slowly’ increase with higher age, especially after the age group 45 to 54. This tendency does not seem to be related to exposure (i.e. that those age groups are more often struck by vehicles in high speed environments) or that the older groups are more frequently struck by heavy vehicles (only the oldest group has an elevated percentage of heavy vehicle involvement).

The combined risk of severe or fatal injuries seems to have a U shape, and the spike of the oldest group is not so salient as for fatalities. To sum up, the most noticeable result is that the risk of fatal injuries spikes for the age group 75+, with over double the risk of fatality, much more than for the age group 65–74. This might indicate that seniors should in safety analysis be divided into two groups: younger and older than 75 years.

Around 36% of the severe or fatally injured pedestrians are 30 years old or younger and 32% are 65 years old or older. The proportion of the respective age groups in the population of Sweden is 37% and 20% [38], i.e. the seniors are overrepresented in fatal accidents. However, this analysis does not take into consideration the exposure or at what speed the pedestrian was struck. It is possible that seniors are over represented as pedestrians in the traffic or that the reason for young children and seniors having a higher risk of severe injuries is that they are generally struck at higher speed (i.e. it is the speed rather than the age that results in the higher risk of severe injuries). To ascertain this, accidents from dataset 1, where the speed limit was included in the accident report, are analyzed ($n = 3600$). The speed limits 110 and 120 are combined due to too few accidents recorded (statistics are not shown for 20 and 40 km/h zones for the same reason). The population is divided into nine age groups: young children (0–6 years old), older children (7–15), adults (16–24, 25–34, 35–44, 45–54, 55–64), seniors (65–74) and older seniors (75+), see Table 3.

The rate of severe and fatal injuries is higher in this sample (i.e. sample with speed limits) compared to dataset 1 (fatal injuries 5.3% compared to 3.3% and severe injuries 22.2% compared to 17.4%). This overrepresentation of more severe accidents might be due to the fact that if the consequence of the accident is more severe (i.e. severe or fatal injuries), then the accident report might be filled in more thoroughly and is therefore more likely to include the current speed limit. It is also interesting that this overreporting of more severe injuries in reports including speed limits seems to vary among the age groups, creating inconsistencies in the fatality risk values between Table 3 and Fig. 4 (where the values in Fig. 4 are more reliable). The risk values in Table 3 are therefore only included to demonstrate this bias.

The main result from this analysis is that the overwhelming majority of the accidents in all age groups occur at locations with a speed limit of 50 km/h (71.5% to 83.4%), and only 4.0% to 15.3% occur at higher speed limits (i.e. 84.7 to 96.0% of the accidents occurred at urban speed limits). Furthermore, ‘only’ 8.2 to 15.0% of the accidents occurred where the speed limit is 30 km/h or below. This ‘low’ proportion at 30 km/h or below is probably a combined effect of low traffic volumes in these streets, and the fact that there is a much lower risk of accidents occurring at 30 km/h compared to 50 km/h [39]. There is a statistically significant difference between the age groups regarding the speed limit distribution ($p < 0.001$, chi square test). However, when reviewing the results in Table 3, those groups with an elevated risk of severe or fatal injuries (according to the more reliable risk values from Fig. 4), i.e. seniors, older seniors and children, are struck at locations with similar or lower speed limits compared to adults. Therefore, this analysis does not support the hypothesis that the higher risk of severe and/or fatal injuries for children and seniors is that they are struck by vehicles in higher speed environments.

Table 3

The proportion of accidents at locations with different speed limits, based on all accidents in dataset 1, where the speed limit was registered in the accident report ($n = 3600$), heavy vehicle involvement is based on all accidents within dataset 1 ($n = 8166$).

Speed limits	Age									Total	Minor injuries	Severe injuries	Fatal injuries
	0–6	7–15	16–24	25–34	35–44	45–54	55–64	65–74	75+				
20 km/h							6%	0.4%	0.2%	4	–	–	–
30 km/h	14.9%	15.0%	10.1%	10.2%	13.2%	10.4%	10.1%	7.8%	9.8%	401	82.5%	14.7%	2.7%
40 km/h		0.2%	0.4%	0.8%				0.4%	0.2%	9	–	–	–
50 km/h	81.2%	72.0%	77.4%	74.9%	71.5%	75.8%	77.9%	80.9%	83.4%	2762	75.0%	21.9%	3.1%
70 km/h	4.0%	9.8%	6.7%	6.1%	8.2%	8.9%	7.5%	6.6%	3.7%	255	54.9%	33.3%	11.8%
90 km/t		2.9%	3.9%	4.9%	4.9%	3.7%	2.6%	3.5%	2.2%	124	32.3%	30.6%	37.1%
110/120 km/t		0.2%	1.5%	3.1%	2.2%	1.2%	1.4%	0.4%	0.4%	45	33.3%	26.7%	40.0%
Total	101	561	793	391	365	326	348	256	459	3600			
Minor injuries	80.2%	79.0%	76.5%	79.0%	74.2%	69.3%	69%	67.2%	56.9%				
Severe injuries	17.8%	18.7%	20.3%	17.4%	20.5%	24.5%	25.9%	27.0%	29.0%				
Fatal injuries	2.0%	2.3%	3.2%	3.6%	5.2%	6.1%	5.2%	5.9%	14.2%				
Heavy vehicles	2.5%	3.5%	3.6%	3.7%	3.0%	4.1%	3.8%	2.9%	5.4%				

5.3. Vehicle type

The data material from the STRADA accident database includes limited information regarding the vehicle type, but only if it refers to a passenger car, truck or a bus (heavy vehicle). Previous research (6) has shown that it is also important if the vehicle type is a SUV, minivan or LTV. The purpose of this chapter is not to analyze the effect the vehicle type has on the resulting injury, but rather if it can be expected to have considerable effects on the results.

Table 4 reveals that there is a slight underrepresentation of severe injuries for heavy vehicles but an overrepresentation of heavy vehicles in fatal accidents ($p < 0.001$, chi square). A comparison of the speed limits of those accidents reveals that the greater proportion of the heavy vehicle accidents is in zones with speed limits of 30 and 70/90/110 km/h, however, there was no statistically significant difference for the speed limit between heavy vehicles and passenger vehicles ($p = 0.79$, chi square). The data also reveals that those struck by heavy vehicles were slightly older compared to those struck by passenger vehicles (42.5 compared to 39.6, $p = 0.050$).

5.4. The combined influence of speed level, age and vehicle type on severity outcome

The previous discussion has shown that both speed and age seem to influence the risk of fatality. Nevertheless, the combined effect of these variables should also be considered. Fig. 5 gives an overview of the injury severity, age, mean speed and vehicle type for dataset 2 (note that dataset 2 is stratified with 19 fatal accidents against 60 non-fatal accidents. In a representative sample, there would be over 500 non-fatal accidents against 19 fatal accidents. The distribution of those accidents within each injury severity group should be similar though).

There does not seem to be any clear pattern for the accidents involving heavy vehicles, probably due to the low number of accidents. Hence, for now they will be considered not to affect the overall picture (i.e. to cause problems when interpreting the other variables). Overall, the most apparent pattern from Fig. 5 is that even though severe injuries and fatalities occur at all ages and in all speed zones, there is a high concentration of those accidents for older seniors. Focusing only on certain speed intervals, it appears that the risk of severe injuries and fatality increases with higher age. This is in line with the findings of previous studies [19,20]. It is harder to see a similar pattern for the speed variable, mostly due to the fact that more than half of the fatal accidents occur at speeds between 40 and 50 km/h; it can be seen for the age group 75+, though. Fatal accidents seem to be rare below the mean speed of 40 km/h. There are only 4 accidents at locations with a higher mean speed than 60 km/h, and all of those have resulted in severe or fatal injuries. The results also clearly demonstrate that the great majority of the accidents occur at locations with urban speed levels (i.e. max 50–60 km/h). Concerning the minor injury accidents, no clear pattern can be seen. The only fact is that they seem to occur between 15 and 55 km/h and that they are relatively more frequent for the younger groups. However, there is high underreporting of minor injuries in the accident statistics [40]. It is interesting that there is a concentration of severe injuries for children and for the oldest group (especially above

the age of 75). When the minor and severe injuries are combined, there is no apparent pattern. When focusing on the fatal accidents only, it is relatively rare that young pedestrians are killed (note that run-over accidents are excluded from this dataset). Regardless, an analysis of dataset 1 shows that young people are frequently killed in traffic, but that those accidents often occur between 7 pm and 7 am and at high speed locations.

The majority of those killed are 75 years or older. For this age group, Fig. 5 indicates that they are struck by vehicles in areas with similar or lower mean speeds than other age groups. This also supports the previous analysis (on speed limits) showing that the higher mortality rate of the elderly is not due to being struck by vehicles in environments with higher speeds, but probably due to being more susceptible to severe injuries and more likely to die from those injuries. If we now combine the severe and fatal injury accidents, it reinforces the same pattern as for the severe injuries with a very high concentration of accidents at ages above 75.

Finally, if we focus more on the speed dimension, severe or fatal injuries seem to be rare at mean speeds below 30 km/h (4 of 48 accidents in dataset 2). The lowest mean speed with a fatal accident is 27 km/h (heavy vehicle involved). The lowest speed, with a passenger car involved is 39 km/h. Nonetheless, severe injuries are quite frequent: 6 accidents between 30 and 35 km/h (of 29 severe injury accidents) and 3 accidents at below the mean speed of 30 km/h. This is around 31% of the severe injury accidents, thereby indicating that the speed limit of 30 km/h is not sufficiently low to prevent severe injury accidents.

To get a better statistical insight into the relationships between these factors, we have created a multinomial logit model. Due to the fact that dataset 2 was collected with an outcome-based strategy, the regression had to be weighted. The results from the weighted multinomial logit model are shown in Table 5. The comparison shows that there is a statistically significant difference for both the mean speed and the age between minor injuries and fatal injuries. However, there is no statistically significant effect for the age variable between severe injuries and fatal injuries (just as the analysis in The influence of speed level on severity outcome section showed). We have run an additional model, where the reference injury group is “minor injuries”. One variable is not statistically significant, i.e. the mean speed does not differ between minor and severe injuries ($p = 0.144$).

We have also tested the combination of (1) minor injuries and severe injuries and (2) severe injuries and fatal injuries. Both models result in statistically significant variables ((1) $p_{age} = 0.008$, $p_{speed} = 0.004$, (2) $p_{age} = 0.005$, $p_{speed} = 0.022$). Finally, we have removed accidents with heavy vehicles from the data, which gives parameters within the 95% confidence interval for the original model, as shown in Table 6.

6. Discussions and conclusions

The analysis shows that both the age of the victim and the mean travel speed of traffic at the accident site have considerable influence on whether the injury of the pedestrian struck by a vehicle is severe or fatal. However, the relation is not statistically significant between (1) severe and fatal injuries for the age variable and (2) minor and severe injuries for the speed variable. The prior lack of significance is unexpected, and when the severe injuries and fatal injuries are combined, the multinomial logit model gives a very high significance level for the age variable ($p_{age} = 0.005$). The second lack of statistical significance is expected since the cumulative curves of the mean speeds do not differ to any great extent. This is strange, though, since higher mean speeds could be expected to result in higher impact speed and consequently more severe injuries. Previous research (for example [22]) shows that a higher impact speed is associated with a higher risk of severe injuries. There are two possible explanations for why we cannot identify a statistically significant difference: (a) our study excludes some accident locations because they have very low traffic volumes. Most of those locations have low speeds, and there is higher underreporting of

Table 4
Demographics for accidents involving heavy vehicles compared to all vehicles (based on dataset 1).

	Passenger vehicles or unknown	Heavy vehicles
Minor injuries	79.5% (6245)	74.8% (229)
Severe injuries	17.5% (1374)	15.0% (46)
Fatal injuries	3.1% (241)	10.1% (31)
20/30 km/h	11.2% (390)	13.3% (15)
40/50 km/h	77.2% (2691)	70.8% (80)
70+ km/h	11.6% (406)	15.9% (18)
Average age of victims	39.6 (7860)	42.5 (306)

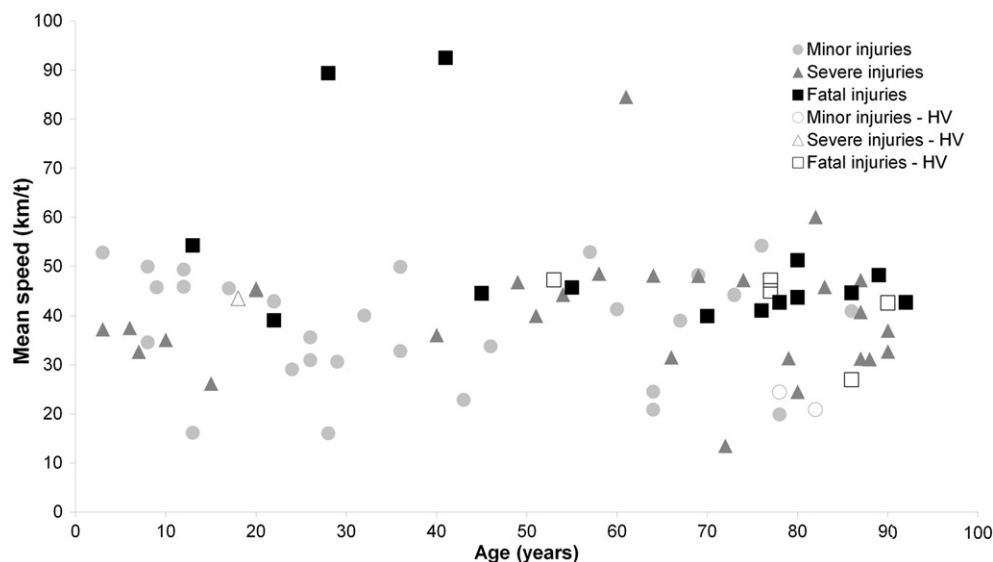


Fig. 5. The severity of the injury by the age of the struck pedestrian and the mean traffic speed at the accident location (HV: heavy vehicle).

minor injuries compared to severe injuries [40]. This underreporting can even be expected to affect the speed distribution within the minor injury group, where there would be higher underreporting for the low speed accidents. Those factors are likely to result in the cumulative curve of mean speeds being shifted to higher speeds, decreasing the difference between the minor injury curve and the severe injury curve. (b) The travel speed of the car involved in the accident differs from the mean speed at the accident location. It is possible that the cars that are involved in severe injury accidents systematically travel at higher speeds, relative to the mean travel speed, compared to those involved in minor injury accidents. Richards et al. [42] showed that excess speed was a contributory factor in a higher proportion of the serious and fatal accidents compared to the minor accidents, indicating that drivers involved in serious accidents likely drive at higher speeds compared to the mean speeds of drivers involved in minor injury accidents (i.e. for a certain mean speed in the street, those involved in serious accidents drive at higher speeds than those involved in minor injury accidents). Even though the dataset Richards et al. [42] used was not limited to pedestrians, it is possible that similar effects may exist for pedestrian accidents.

The age of the struck pedestrian is a highly influential factor. The data clearly shows that the elderly are overrepresented among those who are severely or fatally injured. This is in line with previous research that has shown that seniors are at greater risk of being severely or fatally injured in an accident [1,25,43]. The age categorization of the elderly is often set at 65 and older. Our data, however, shows that the steepest increase in the risk of fatal injuries is after the age of 75. Analysis of the cumulative age curves in Fig. 3 and fatality risk presented in Fig. 4 indicates that the risk might start to increase from the age of around 40 to 45, which is in line with Gustafsson and Thulin [44] who showed increased fatality risk already for the age group 45 to 64, and Kim et al. [43] were

the proportions of fatalities started to increase from the age group 55 to 64. The data also shows an increase in risk of severe injuries for the youngest age groups, which is in agreement with previous results [11, 44]. This therefore indicates that the risk of severe injuries vis-à-vis age is not necessarily a constantly increasing function, but might be a U-shaped function.

When applying results like this, it is of uttermost importance to consider where the accidents occur, as they are influenced by the exposure, accident risk and injury risk. Hence this should affect the areas to which we should direct our countermeasures (the areas with most of the severe and fatal accidents are the areas with the greatest potential to reduce the number of fatal accidents). Our analysis showed that fatal accidents where the mean speed was below 39 km/h were rare, 1 of total of 19 accidents; the person in question was 86 years old and struck by a heavy vehicle (note this study excludes run-over accidents, as they can be fatal at much lower speeds). Findings by Leaf and Preusser [31] show that the proportion of fatal accidents that occur at speed limits below 40 km/h is 10%, i.e. somewhat higher than in our study (5.8%), and less than 1% below the speed limit of 32 km/h; this study includes run-over accidents that might explain higher proportions. This raises the question of whether this is due to exposure or if a speed level of 40 km/h results in a sufficiently low impact speed so that most pedestrians struck will survive. Our analysis showed that 10.3% of the severe injury accidents occurred at locations with mean speeds below 30 km/h, and 20.7% at locations with mean speeds between 30 and 35 km/h. In datamaterial from the USA [10], 31.7% of the severe injuries (non-fatal AIS4+) occurred at impact speeds below 32 km/h, and in datamaterial from the United Kingdom [45] the proportion of severe injuries that occurred at impact speeds below 30 km/h was 32.7%. Given that we are comparing mean speed to impact speed, those proportions are remarkably similar. This indicates that if severe injuries are to be

Table 5

The parameters from the weighted multinomial logit model. The reference injury severity is for 'fatal accidents' due to the fact that it has the highest reporting degree [41].

Injury severity		Estimate	Standard error	p value	Lower limit	Upper limit
Minor injuries	Intercept	9.006	1.656	<0.001		
	Speed	−0.086	0.030	0.004	−0.145	−0.028
	Age	−0.039	0.013	0.004	−0.065	−0.013
Severe injuries	Intercept	4.965	1.526	0.011		
	Speed	−0.050	0.025	0.042	−0.098	−0.002
	Age	−0.020	0.013	0.120	−0.046	0.005

Table 6

The parameters from the weighted multinomial logit model without the accidents involving heavy vehicles. The reference injury severity is 'fatal accidents'.

Injury severity		Estimate	Standard error	p value	Lower limit	Upper limit
Minor injuries	Intercept	8.680	1.700	<0.001		
	Speed	−0.080	0.030	0.009	−0.139	−0.020
	Age	−0.034	0.014	0.016	−0.062	−0.006
Severe injuries	Intercept	4.935	1.602	0.017		
	Speed	−0.055	0.026	0.036	−0.107	−0.004
	Age	−0.011	0.014	0.430	−0.038	0.016

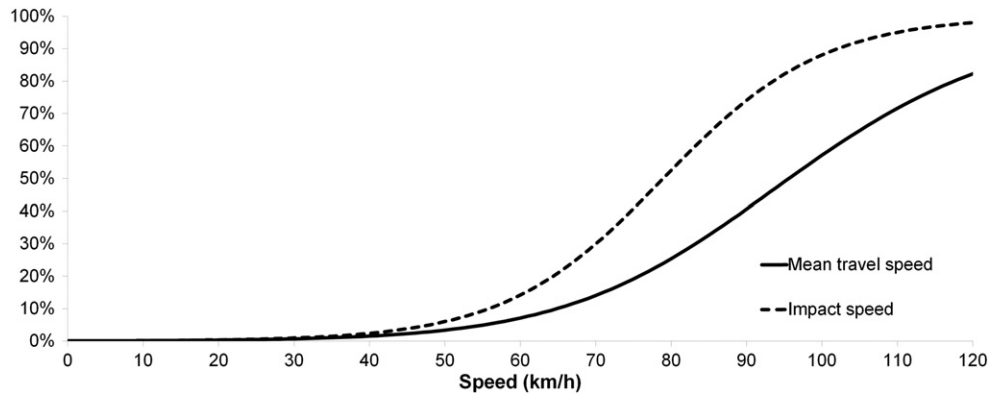


Fig. 6. Comparison between a fatality risk curve based on impact speed [9] and a fatality risk curve based on mean travel speed (our study) for 40 year old victims.

avoided, 30 km/h might not be a sufficiently low mean travel speed, thereby contradicting the 'common' belief of traffic planners that 30 km/h is a 'safe speed'. Furthermore, the cumulative curves of the mean speed indicate that the risk of severe injuries increases when the mean speed exceeds 25 km/h and the risk of fatal injuries increases when the mean speed exceeds 40 km/h. If, based on this, the mean speed is reduced through some speed-reducing measures, then this model and the power model [39] predict that the number of severe and fatal accidents (and all accidents) would decrease.

Kröyer et al. [27] show that in order to understand how speed changes affect the fatality risk, the concept of relative risk is often more appropriate than viewing absolute risk values (such as those that can be extrapolated from these models). This is important if the risk values presented here are to be used. The relative risk ratio demonstrates that the fatality risk is sensitive to the mean travel speed, but, as with the relative ratios for the impact speed [27], the relative effect of reducing (or increasing) the mean speed by 10 km/h is similar for both 30 km/h and 50 km/h base speeds. This means that, given the fact that 63% of the fatal accidents occur at locations with mean travel speeds between 40 and 50 km/h, it is in this speed environment (most probably speed limit of 50 km/h) where lowering the speed will save the greatest number of lives. It should be kept in mind that speed has several other effects for the society, e.g. on exposure, subjective safety, risk of an accident occurring, travel time, sustainability, environmental effects, and social equity. However, those are outside the scope of this work.

There is a complex relation between the impact speed and the mean travel speed. Fig. 6 shows a comparison between two such risk curves for 40 year old pedestrians (model for impact speed based on Rosén and Sander [9]). As expected, the risk curve for the mean travel speed shows lower fatality risk compared to the impact speed; the risk at a mean speed of 45 km/h is the same as at an impact speed of 40 km/h, i.e. a 5 km/h speed difference between the curves. At 70 km/h this difference increases up to around 10 km/h. This difference is due to the fact that the car driver often manages to reduce the speed before the collision occurs. Pasanen and Rosén [32] and Rosén and Sander [9] performed logistic regression on material from the GIDAS database for registered impact speed and travel speed that resulted in a 7 km/h speed difference for the prior example and around 14 km/h for the latter example; however the model was for all age groups. This difference is therefore in line with prior research and demonstrates that the risk of fatality is sensitive to both the mean travel speed and the impact speed.

There are a few limitations to this study that should be brought up: The precision and accuracy of the accident reports vary. Since this study is dependent on knowing the precise location of the accident and which traffic flow was involved in the accident, it is vulnerable to errors in the accident reports. To counteract this, every accident report was thoroughly read and the accident was excluded if the quality was deemed questionable. The Swedish hospitals changed injury classification from

AIS1990 to AIS2005 on the 1st of January 2007. Differences in the severity estimation for some injury types resulting from updating the AIS scale could affect whether an accident is classified as a minor injury or a severe injury. The accident data material is stratified and there are missing cases for minor injuries at low speeds (general underreporting of minor injury accidents). It is possible that the speed level at the accident location changed between the time of the accident and the time of our speed measurement. To compensate for this, the accident location was 'scanned' for possible recent changes that could have affected the speed level. Also, the accident reports were searched for abnormal situations that could have influenced the speed level. This study focuses on mean travel speed, i.e. it does not take into consideration the speed of the vehicle involved in the accident. Finally, the speed measurements were performed in only the most southern part of Sweden; there might well be differences between geographical areas.

To sum up, the data indicates that fatal accidents (excluding run-over accidents) are rare at mean travel speeds below 40 km/h, while severe injury accidents are quite frequent at mean speeds below 35 km/h but rare at mean travel speeds below 25 km/h. Therefore the current speed policies (frequently 30 and 50 km/h speed limits in urban areas) might need revision. Furthermore, this study has shown that both the mean travel speed and age have considerable effects on the injury severity and risk of fatality for a pedestrian struck by a motor vehicle. It also shows how important it is not to dismiss either of these two variables when analyzing injury severity in accidents involving pedestrians. There is a great overrepresentation of the elderly, especially those older than 75 years, among those who are severely or fatally injured and they have higher risk of severe or fatal injuries.

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